*Biomorphic Analog Neural Circuitry**

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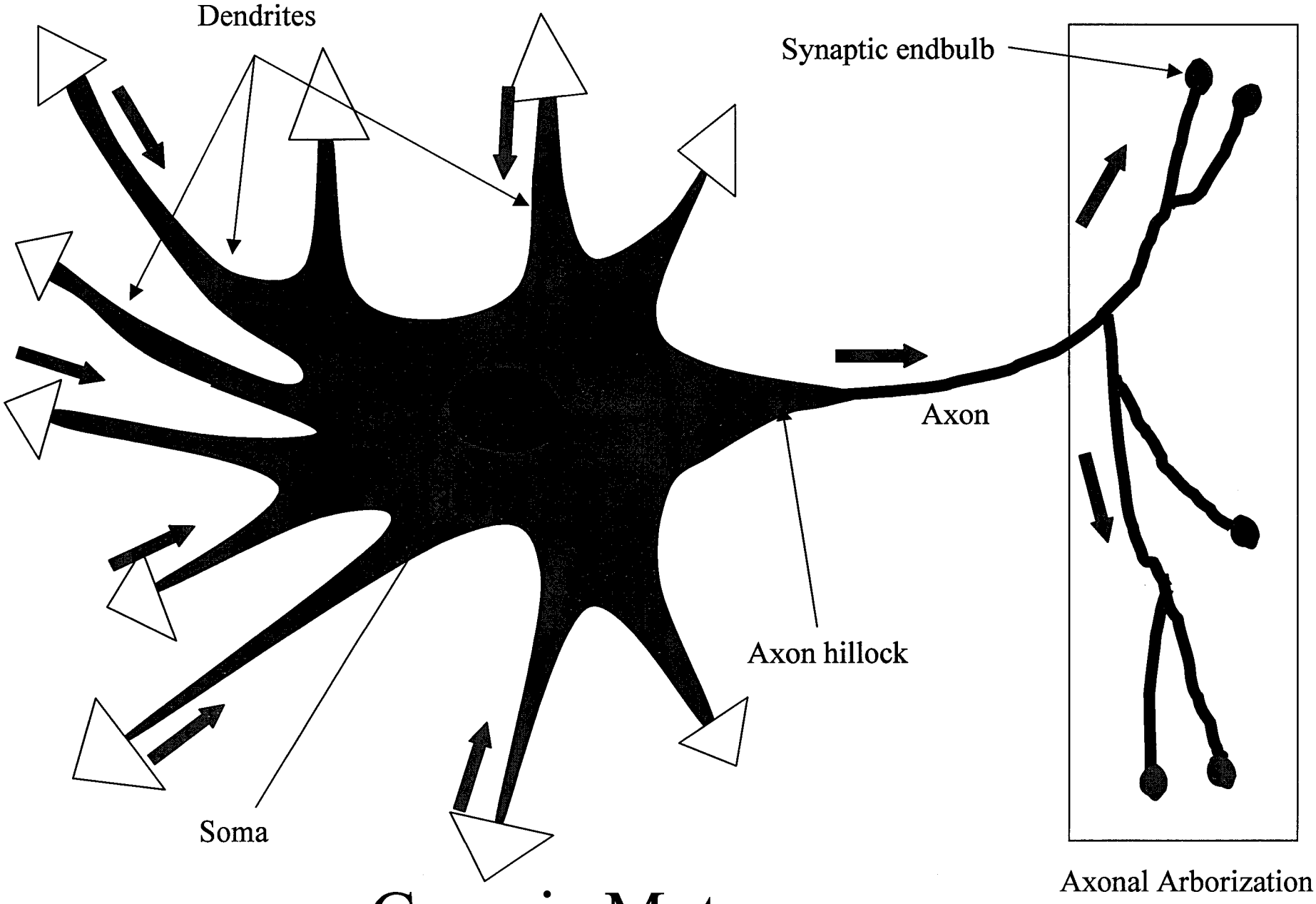
Outline of Presentation

- Introduction
- Motivation
- Neurons (wet and dry)
- Spiking Neuron Model
- New Spiking Neuron Circuit
- New Synapto-dendritic Circuit
- Pulse-Coupled Neural Network chip (PCNN)
- Conclusion

Motivation: Biological Inspiration

- Evolution has produced systems that are extremely efficient and compact yet computationally very powerful.
- By examining these systems, engineering can get insight into solving difficult problems readily solved in biology.
- Implementation strategies must consider the different building blocks between biology and engineering and take advantage of the strengths of electronics and integrated devices.
- Biology's building blocks for intelligence are neurons
- Engineering's building blocks for compact computation are silicon integrated circuits implemented with transistors



Generic Motoneuron

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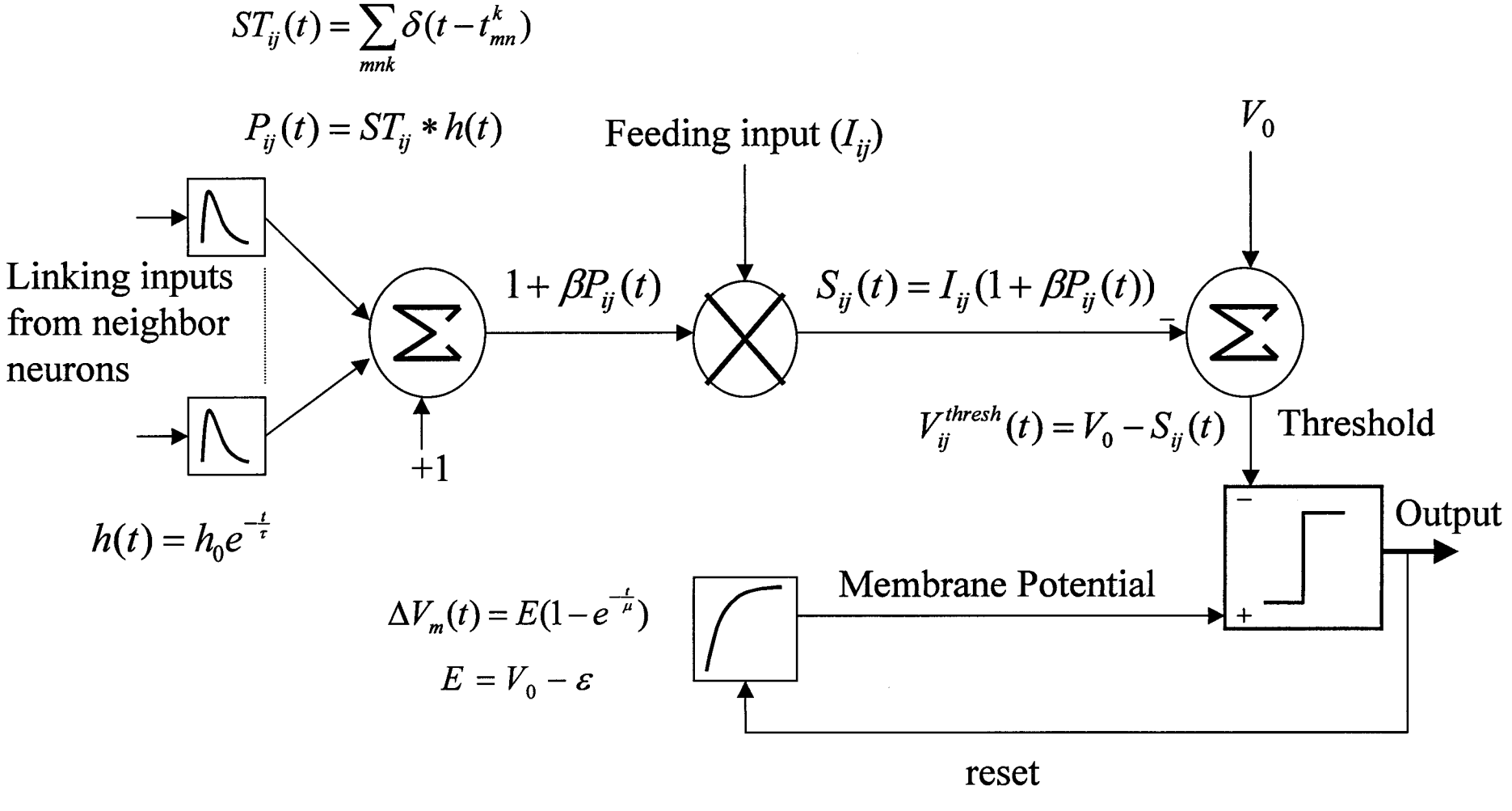
Biological Neurons

- Neurons are composed of dendrites, the soma, and axon.
- Spikes in the membrane potential are generated by voltage-dependent ionic channels.
- The spiking rate of the neuron is dependent on the action potentials impinging upon the soma from the dendritic arborization.

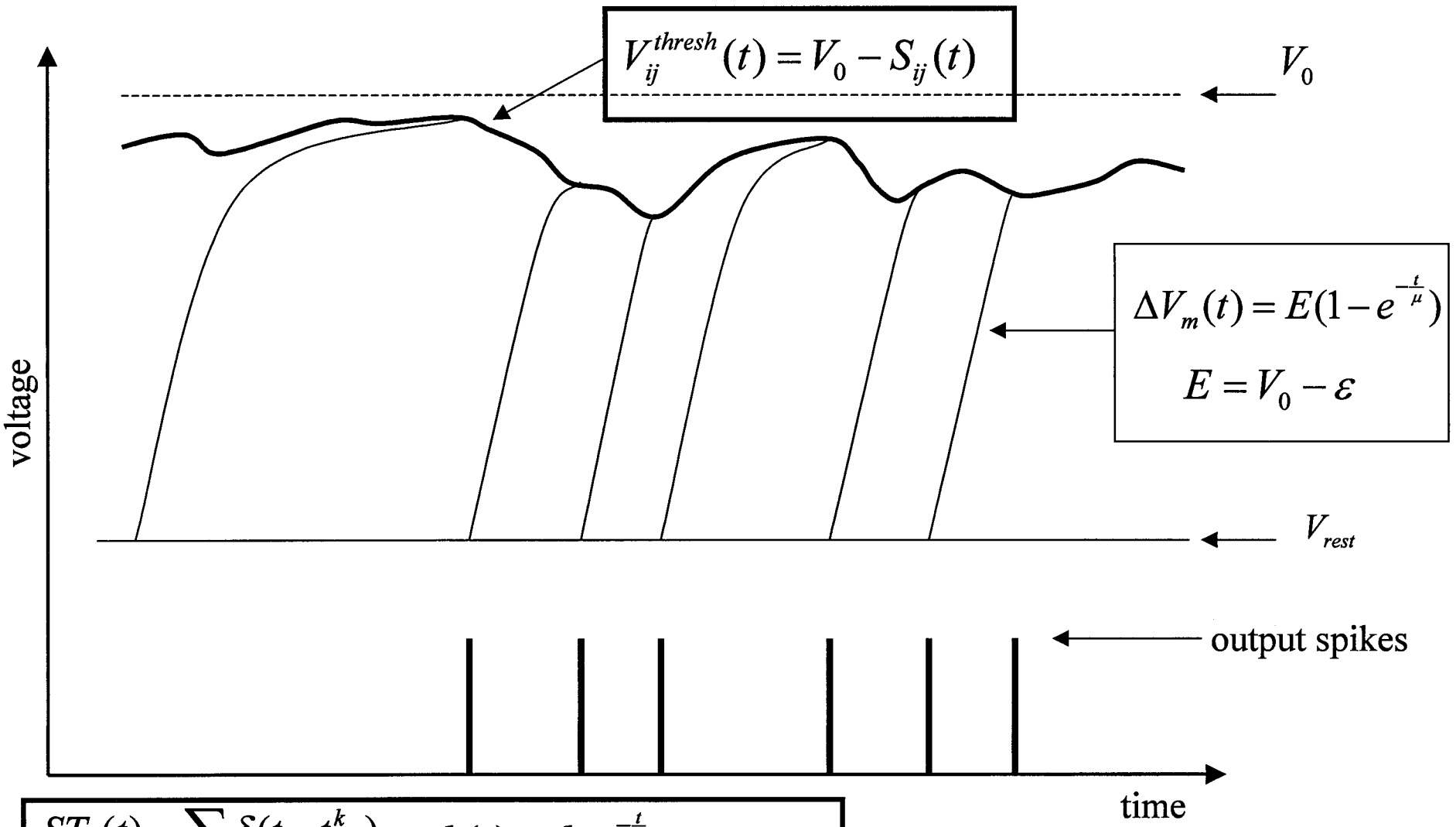
Silicon Neuron Circuits

- Based on some neuron model, e.g. Hodgkin and Huxley
- Seek to replicate biological neuron behavior
- High-order neuron emulation leads to circuit complexity
- One must decide what aspects of behavior are essential to model
- Computational power is achieved both through individual neurons and networks of neurons
- System trade-off between high-order neuron behavior and large network behavior
- A complex neuron forces a smaller network, while a simple neuron allows a larger network.

Diagram of Biomorphic Spiking Neuron Model



μ = membrane time constant
τ = synapto-dendritic time constant

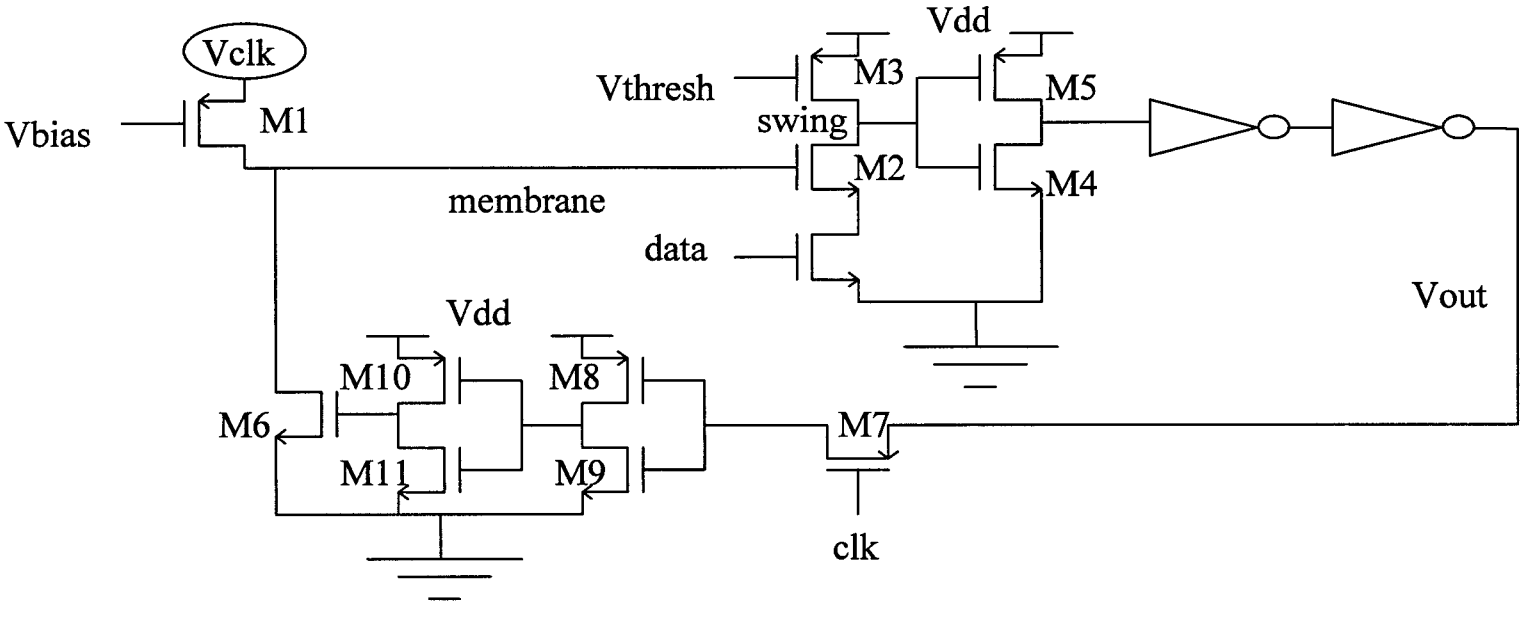


$$ST_{ij}(t) = \sum_{mnk} \delta(t - t_{mn}^{k}) \qquad h(t) = h_0 e^{-\frac{t}{\tau}}$$

$$P_{ij}(t) = ST_{ij} * h(t) \qquad S_{ij}(t) = I_{ij}(1 + \beta P_{ij}(t))$$

μ = membrane time constant
τ = synapto-dendritic time constant

Dynamics of Biomorphic Spiking Neuron Model



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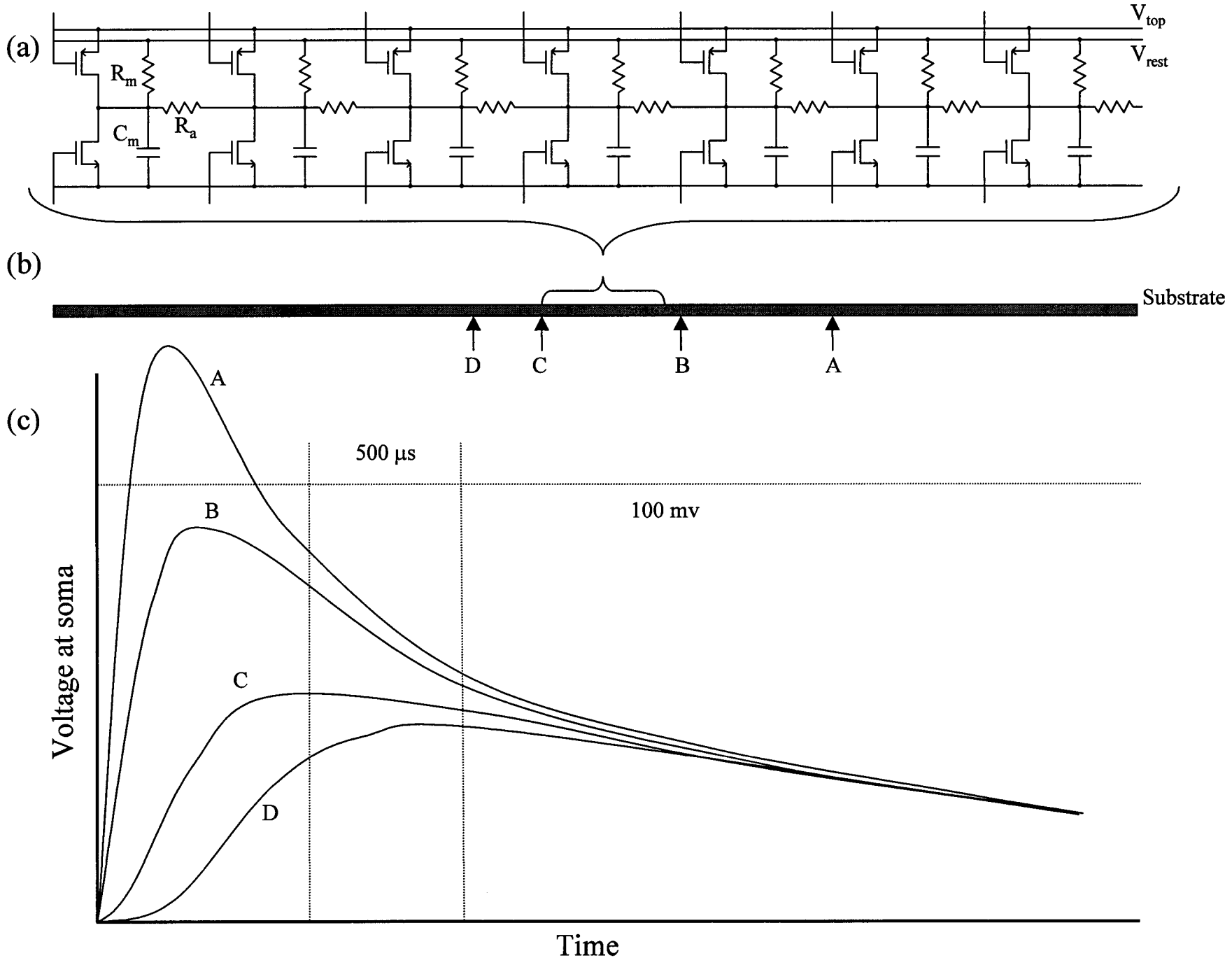
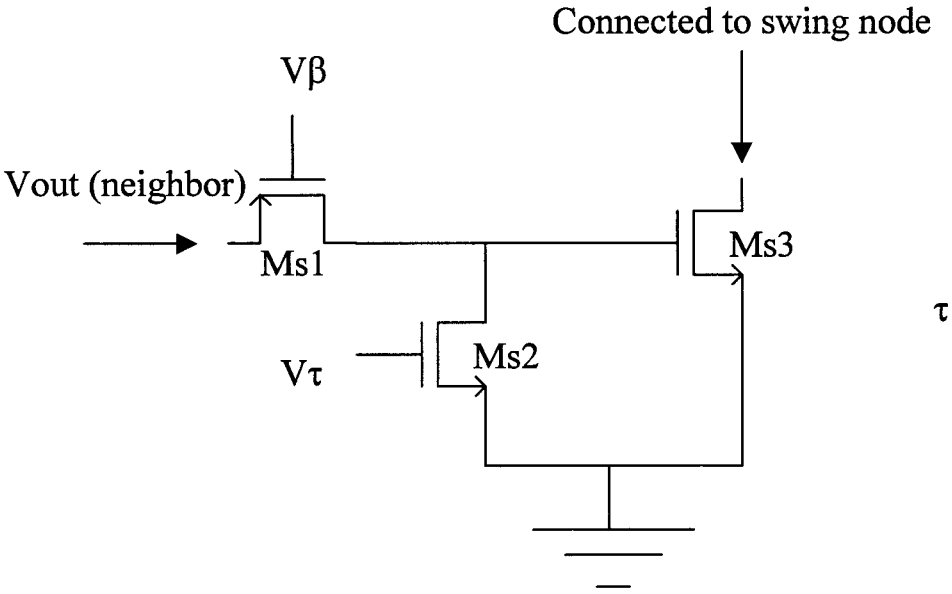
Biomorphic Spiking Neuron Circuit and HSPICE Simulation


(a)
V_{top}
V_{rest}
R_m
C_m
R_a
(b)
Substrate
D
C
B
A
(c)
A
500 µs
B
100 mv
C
D
Voltage at soma
Time

β



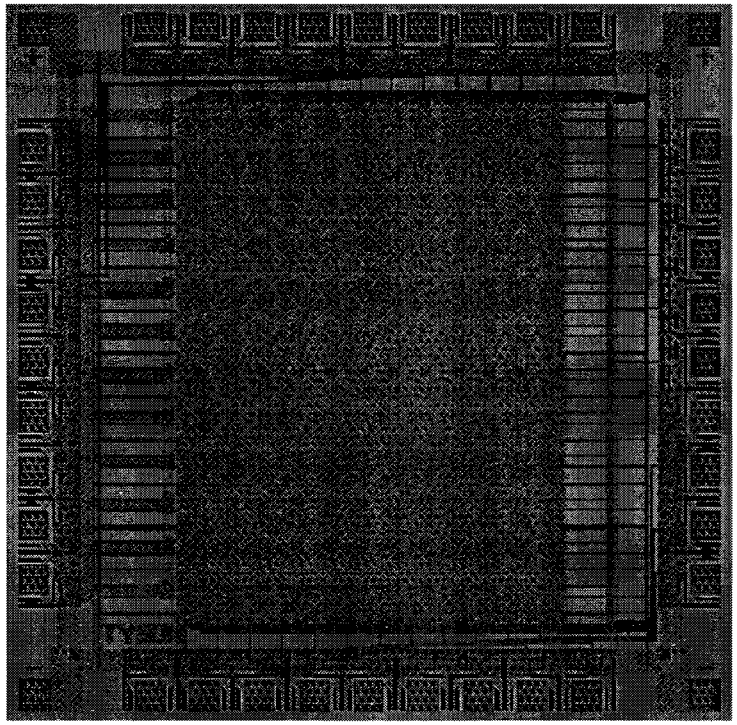
τ

Synapto-dendritic Circuit Diagram and HSPICE Simulations

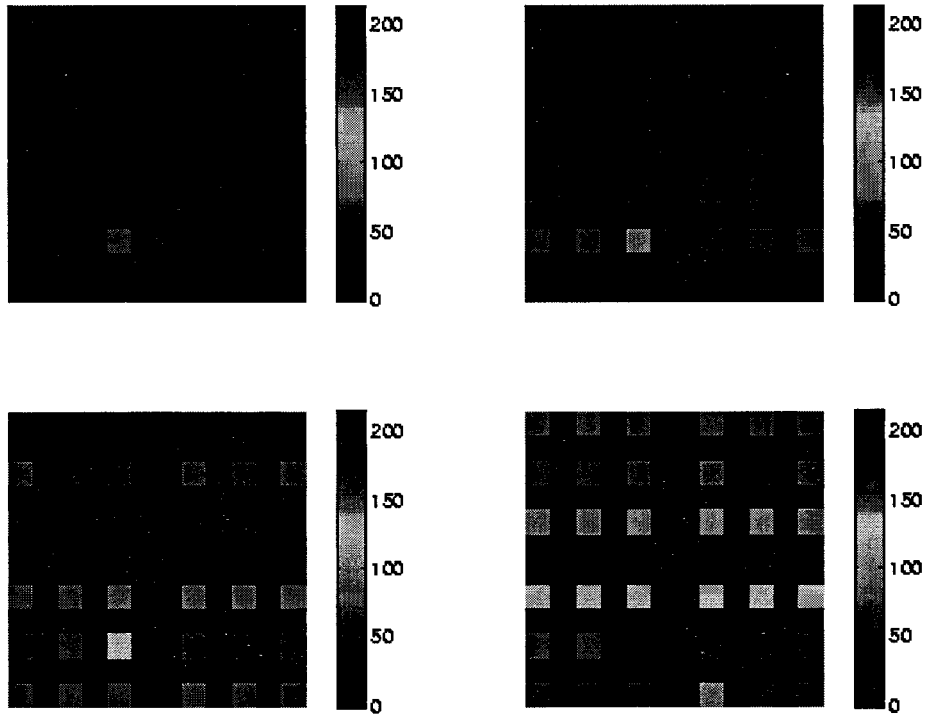
PCNN Chip

- 12 x 12 array of biomorphic spiking neurons was fabricated in a 1.2 μm CMOS process through MOSIS
- Test results indicated that neuron circuits worked but were poorly matched due to process variation, especially significant for devices in the subthreshold regime.
- Poor matching may not be a problem with the introduction of Hebbian or other type of learning.
- Need to adapt algorithms to take advantage of variability similar to biological systems

Layout of PCNN Chip



Output of PCNN Chip for Decreasing Thresholds



Conclusion

- The building block of biological intelligence is the neuron.
- Silicon neurons model biological complexity to different degrees, trading realism for simplicity.
- A set of biomorphic analog circuits has been designed to implement a spiking neuron model with synapto-dendritic input connections and threshold-modulated spiking frequency.
- The spiking neuron circuit and synapto-dendritic circuit efficiently model important neuronal behaviors while achieving low-power and compact silicon area.
- The biomorphic analog circuits offer a good trade-off between biological realism and implementation economy.